

LUBRICATION

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Thin Oil Films

THE underlying principles of everyday lubrication are now so well understood that an engineer has a relatively simple problem when called upon to design a bearing which will operate satisfactorily under specified conditions. His interest is solely concerned with the behavior of the bearing when running at a specified speed under a specified load. He thinks only in terms of full fluid film lubrication and sees to it that provision is made for supplying the rubbing surfaces of the bearing at all times with an oil of a suitable type and of a viscosity suited to the operating conditions. Under these circumstances he is able to state with considerable confidence that the coefficient of running friction of his bearing will be a number preceded by one or two zeros.

And yet, although he has theoretical reasons for believing that a correctly designed bearing should run indefinitely without visible wear, he is not optimistic enough to expect it to do so in actual operation.

What Causes Wear in Bearings?

Bearings do not always operate under fluid film conditions. When a machine is shut down the static load may squeeze out the oil until the film separating the metal surfaces is extremely thin. On starting up, there is a delay in the formation of the full fluid film; it is during this period that wear of the rubbing surfaces takes place. This wear, however, is not necessarily of a serious type, since no matter how severe the squeezing-out action, the opposed surfaces still carry an adsorbed layer of oil which is at least one molecule thick; so long as this layer remains attached to the metal, no clean contact can take place.

An examination of the rubbed areas after long-continued operation will show that the wear has been somewhat of a polishing process, the surface of the metal exhibiting a mirror-smooth patina. Sub-microscopic projections have been worn down and sub-microscopic valleys have been filled in. This process of running in combines the agencies of actual wear and surface flow. The wear, however, is to be regarded merely as the result of a slow removal of minute irregularities projecting above the general level, and the total amount of actual metal lost may be very small indeed. Surface flow is generally recognized as the phenomenon responsible for the formation of the desirable Beilby layer.

Surface Finish

Perfect finish of any metallic surface is an ideal which is impossible to achieve. The most beautifully finished surface plate is covered with "high spots," and the best that can be done is to increase the total number of high spots, and to reduce the difference in level between these plateaus and the intervening valleys. By extremely nice workmanship it is possible to prepare a flat surface, say a 2-inch diameter block of hard steel, true to about $1/10$ the wave length of sodium light. Reduced to a more usual system of measurement, this means that the difference in level between the top of a plateau and the bottom of a valley is about two-millionths of an inch.

This is a minute distance, according to our usual conception of size, but it is over twenty times the length of an average molecule of oil. The nearest approach to an absolutely true plane surface is the central portion of the surface of a very large pool of clean mercury stand-

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ing in a dish on a vibrationless table. Other very true surfaces may be produced by cleaving certain crystals, such as calcite.

What is a Polished Surface?

In practical service solid friction can be most effectively counteracted by lubrication where the moving parts are as smooth and true as possible in geometrical figure. As perfect smoothness is approached by finishing, surface irregularities are reduced. An absolutely smooth surface would be invisible. This is most closely approximated by a perfectly still surface of clean mercury. Here the only departure from perfect smoothness would be due to the surface agitation of the molecules, an effect of temperature; but this agitation, of course, would be far too minute for the eye to perceive.

In an attempt to approach a natural smooth surface by artificial means, metallic surfaces essential to machine operation are ground and polished. The gross irregularities of the surfaces are reduced by grinding, finer and finer abrasives being used as the operation proceeds.

Under the microscope it can be seen that even the most finely ground surface is covered with scratches; the better the grinding, the finer the scratches. Beilby has shown that polishing and grinding are distinct processes. In the polishing process, the extreme outer skin of the surface is caused to flow. Minute projections above the average surface are worn down, and minute furrows are filled up or bridged over. It is rather startling to realize how mobile the surface molecules of a solid have been proved to be, as evidenced by the flow phenomena during polishing, but it must not be forgotten that even with the use of jeweller's rouge on a soft pad, high values of unit pressure may be reached.

In modern practice, the final polishing proc-

ess is more conveniently and economically done with the bearings and journals in place. They are allowed to rub against each other, with a lubricant between them, the effect of this "running in" process being to bed them thoroughly together, and to produce on the

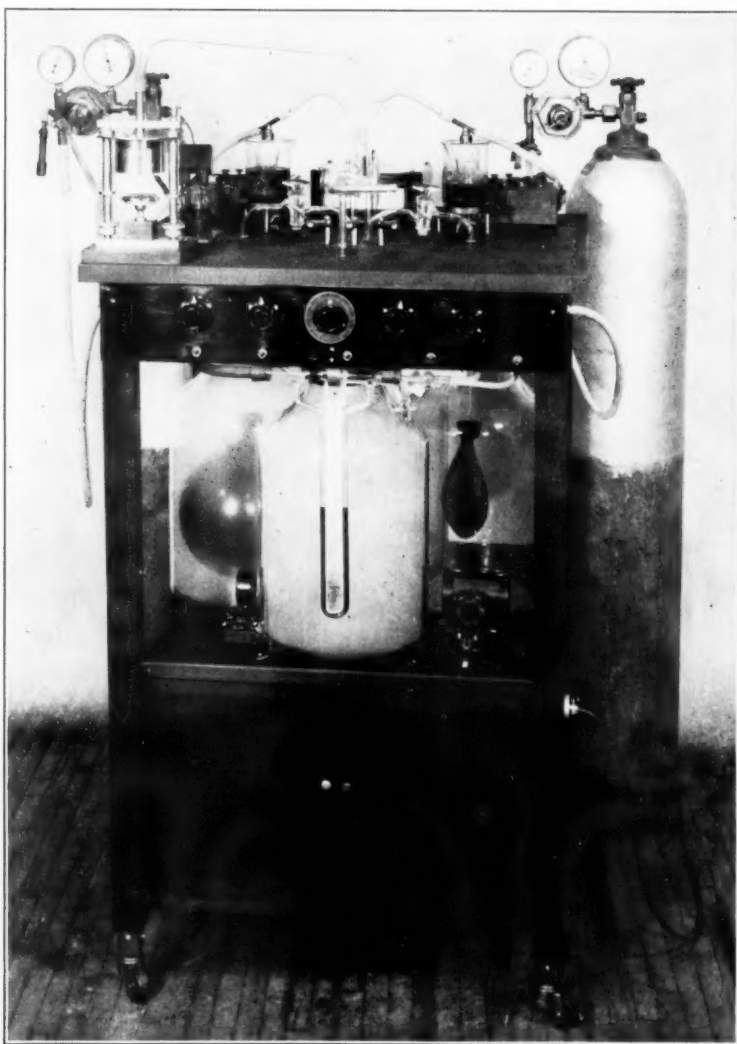


Fig. 1—General view of apparatus for making oil fog and depositing thin films.

surfaces a very high polish.

After the rubbing surfaces have been thoroughly run in, the rate of wear in normal operation falls to a negligible figure and the question then arises as to the causes for abnormal wear, the visible evidence for which is scuffing and abrasion. If we leave out of the picture such accidental agencies as the presence of abrasive material, there remains only breakdown of the oil film between the opposed rubbing surfaces

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as the blanket cause for bearing failure. However, oil film rupture is not likely to occur in a well run-in and properly operated bearing, but if it once starts, the damage to the surfaces is of a very serious nature. So long as the opposed metal parts are at all times separated by at least two molecular layers of oil there can be no wear of the type known as abrasion, or scuffing. If the mechanical attack at the contact areas of metals rubbing together becomes severe enough to remove the ultimate protecting film, the clean metals will seize, causing irreparable damage to the surfaces. This seizure, in fact, involves incipient welding, resulting in the gross removal of metal.

Polish wear, on the other hand, is due to the smooth removal of surface molecules, and occurs when the separating oil film has an average thickness less than the average height of surface irregularities. Polish wear is beneficial and is the process made use of in a running-in operating. It is obvious that the better the surface finish, the thinner may be the separating oil film.

The ideal case, as indicated above, would be two perfect surfaces separated by a double molecular layer of lubricant. Since perfect surfaces are unattainable, we have to recognize the fact that the working film between rubbing surfaces must be considerably thicker than this. The rise in the coefficient of friction on passing from fluid film to boundary film conditions is quite rapid which means a rapid increase in the rate of dissipation of energy at the rub spots. Unless prompt steps are taken to re-establish fluid film conditions, the ultimate protecting film adsorbed on the surfaces is likely to be rubbed off, thus bringing clean metal into contact.

The question we are now to consider is—what happens at surfaces in contact when there is absolutely no oil film present between them.

WHAT IS A CLEAN SURFACE?

Absolute cleanliness is an ideal to aim at, but an extremely difficult one to realize. It means in effect the complete absence of any foreign material whatsoever, and is a term reserved almost exclusively to describe the condition of the surface of a body, rather than its volume purity. For instance, it is possible to distill water to a high state of purity, but quite difficult to maintain a clean surface on water exposed to the ordinary atmosphere of a room. After a short time, a film of greasy matter will form on the water surface, forming an adsorbed layer, possibly only a molecule thick, but quite sufficient to modify very radically the physical state of the free surface.

An oxidized metal such as iron is extremely difficult to clean, since in an ordinary atmos-

phere containing water vapor and oxygen, a film of oxide will form on the oil-free surface almost instantaneously. If it were possible to produce a clean surface on iron, it could be easily wet by mercury. It is stated in the literature that if a rod of steel be broken beneath the surface of pure mercury, the fractured surfaces become amalgamated, proving the state of absolute cleanliness of the newly exposed metal surfaces.

In general, the water wetting test is a useful and simple way of proving whether a surface is free from oil. If a surface, say of glass or steel, carries a film of oil even as thin as one molecule, and is then flooded with water, and shaken, the water will run off, leaving the surface apparently dry. But if an adherent film of water remains, it proves that the surface is relatively free from oil or grease.

WHY DOES AN OIL FILM BREAK DOWN?

The normal state of a surface is one of contamination, and it is difficult both to clean it, and to keep it clean. Further, such contaminated surfaces when brought into contact do not actually touch. The only way of making them actually touch is to remove the contaminating films. It is rather interesting to note that it is impossible to remove the last trace of oil from a metal surface by means of solvents. Suppose we flood the surface of a piece of polished steel with oil, and then wash it in several changes of carbon tetrachloride, or benzene, or acetone. To all outward appearances, all the oil will be removed by the solvent, but the water wetting test will show that a strongly adherent film still remains on the surface.

This adsorbed film, which resists perfectly the action of a solvent, is easily removed, however, by a simple polishing process. If the steel surface is rubbed with a mixture of chromic oxide and water, followed by a treatment with the dry powder, no trace of oil will remain, as can be proved by the water wetting test, or by rubbing the cleaned metals together, in which case deep scoring will result.

Returning now to our original question as to the cause of mechanical breakdown of an oil film it will be easily seen that the mechanical work of friction at the rubbing surfaces provides an entirely reasonable explanation. The adsorbed oil film is continually being removed, and replaced just as rapidly as it is removed by virtue of the forces of attraction between the free surface of the metal and the oil molecules. So long as the friction is not excessive, the rate of removal of the film does not exceed its rate of renewal, but if either the load or the speed is increased to a point where the work

of friction reaches a critical value, clean metal contact occurs, with resulting abrasion.

RELATION OF FILM BREAKDOWN TO SURFACE FINISH

This is rather an academic question, since oftentimes all that can be done is to delay the inevitable breakdown when the destructive agencies become too severe.

If we examine the problem more closely and inquire what practical means are available for decreasing the risk of breakdown, we find that it is a problem involving both the oil and the perfection of finish of the metal surfaces. The petroleum industry is prepared to furnish lubricants which will meet satisfactorily every class of service, but it is felt that the machinery industry has largely overlooked the great gain in safety and power saving which follows the use of properly run-in rubbing surfaces.

It has previously been pointed out that the most perfect surface which it is possible to produce is still very far from being geometrically true. It is covered with high spots or plateaus above the general level, and these constitute a potential source of danger when the surfaces approach very closely.

One of the most difficult problems of lubrication which has developed in the last few years is in connection with hypoid gears. Intensity of load and speed of rubbing are both high, which means that the work dissipated in friction is also high. In other words, we have high power losses and we have wear. Polish wear is desirable, but abrasive wear should be avoided, and this constitutes the real problem. Under the high loading the oil film between the high spots becomes extremely thin. So long as it exists at all there can be no clean metal contact, and

therefore no abrasion, but this state of affairs can only continue so long as the rate of removal of the film does not exceed its rate of renewal.

Extreme pressure lubricants such as are used for hypoid gears where the intensity of loading is very high, may with advantage be

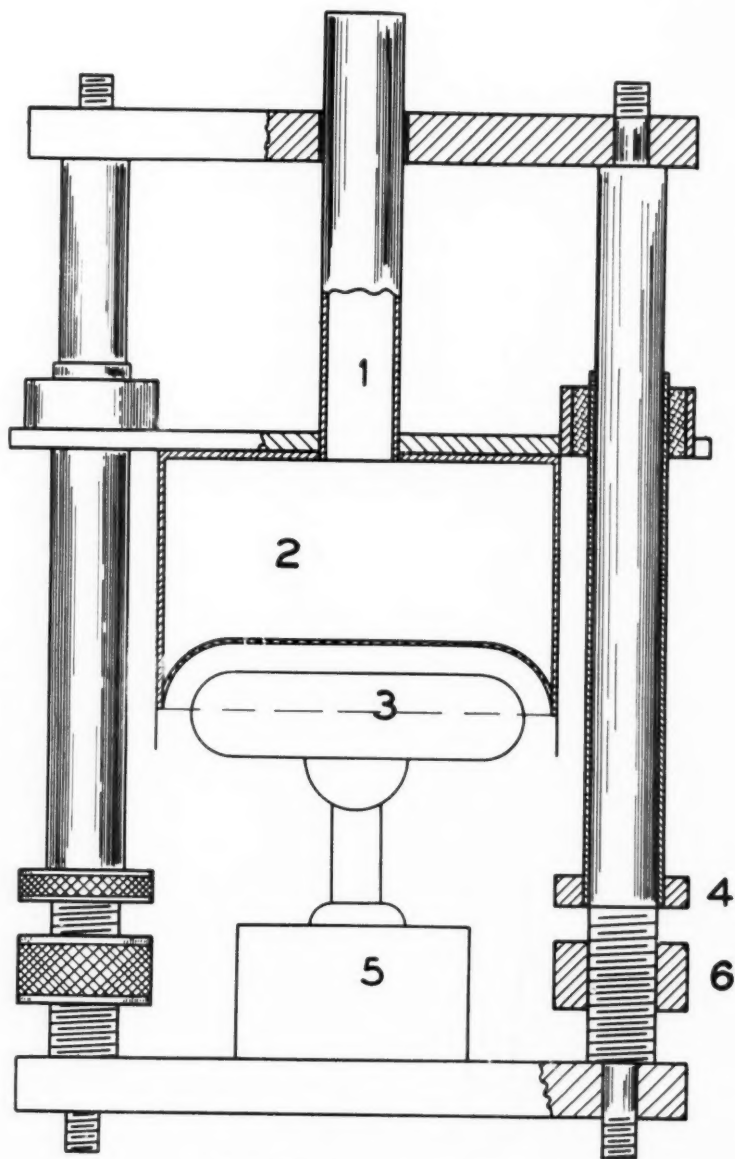


Fig. 2—Sketch of log deposition apparatus.

used for the pre-conditioning of bearing surfaces. This type of lubricant contains sulphur or chlorine which will react with the metal when the temperature, due to the heat of friction becomes high enough, forming a tough,

resistant film. The very fact that high loads may be used with safety in the running-in operation means that in a comparatively short time high spots will be polished down, and the surface will acquire the extreme burnish so greatly desired since it spells both safety and lowered power loss. The extreme pressure oil is then replaced by an undoped lubricant of a viscosity suited to the load which is to be carried.

WHAT IS A THIN OIL FILM?

Since it is obvious that the term "Thin" is very elastic, it is necessary to set limits for its dimensional value before we can investigate the properties and mechanical behavior of lubricat-

ing-off process. Not only would the remaining oil film be progressively thicker toward the lower edge, but the thickness of even the thinnest portion would be far greater than we require. At first experiments were made on an evaporation method, in which a very weak solution of the test oil in benzene was applied to the steel surface; the solvent evaporating to leave the oil behind. Unfortunately, however, although we can lay down a known amount of oil by this method, the final film is not uniform in thickness.

The Oil Fog Method

We then found it was possible to produce a fog of extremely small particles of oil by means

TABLE I
Thickness and Color of Multilayer Films of Barium Stearate

<i>No. of Layers</i>	<i>Thickness (millionths of 1 cm.)</i>	<i>Interference Color</i>
21	5.1	Yellow-Brown
41	10.0	Dark Blue
61	14.9	Light Blue
81	19.8	Yellow
101	24.6	Red
121	29.5	Blue
141	34.4	Green
161	39.3	Red-Yellow

ing films of this type. The logical question to ask is, how thin must an oil film be in order that the component oil molecules lose their mobility. The reason for this question lies in the fact that we propose to investigate the protective action of a thin film subjected to severe mechanical punishment. Above a certain minimum thickness we may expect the oil molecules immediately adjacent to the high spot areas where the squeezing-out action is a maximum, to flow in as soon as the excess pressure is relieved. Below this minimum thickness the protecting film is rubbed off faster than it can be replaced by flow.

Evidence presented later, as shown graphically in Figure 4, indicates that under favorable circumstances a considerable measure of protection is afforded by films thinner than one-millionth of an inch. So in this investigation a thin film will be regarded as one having a thickness less than $1/1,000,000$ inch.

How to Produce a Thin Oil Film

Our problem is to apply to a clean, polished surface of metal, say steel, an oil film having a uniform thickness of one-millionth of an inch, or one-tenth millionth of an inch, or any other specified thickness in this extremely thin region. This cannot be done by any dipping and drain-

ing of a special form of atomizer; furthermore, one of the characteristics of such a fog is, that the tiny droplets composing it are positively charged. So by suspending our steel plate in this fog and then charging it negatively, the fog droplets will be attracted to stick thereto. After proving this theory a way was opened to a method of depositing an oil film of uniform thickness.

It is interesting for a moment to look into some of the phenomena connected with this oil fog method. In the first place, the oil droplets, being mechanically produced, have the same composition as the bulk oil. Nitrogen is used at the atomizer nozzle, as well as for flushing out the apparatus. Thus there is no risk of oxidizing the finely divided oil. The rate at which an oil film builds up on a metal surface is found to depend on the nature of the oil, the density of the fog, and the electrical potential gradient at the deposition plate. Very fortunately, too, the rate of deposition is found to be constant, for any fixed conditions, which means that the thickness of film deposited in one minute is one-tenth that of the film laid down in ten minutes. Of course, careful attention must be given to such matters as the density of the fog, the rate of flow over the metal deposition plate, and the voltage applied.

Some Details of the Fog Deposition Method

Oils of all S.A.E. grades are atomized with the same ease providing they are brought to the same viscosity by adjustment of the temperature in the atomizing bottle. The general practice is to atomize an S.A.E. 10 oil at room temperature, say 75 degrees Fahr., and then to find from the A.S.T.M. chart to what temperatures the other S.A.E. grades must be adjusted, in order that their viscosities will be the same.

Concentration, or fog density, is easily adjusted to a constant value by photoelectric means. The fog as produced is led first into a large glass bottle of five gallons capacity and from this, into a similar container called the "working bottle." At opposite sides of this bottle are arranged a Weston Photronic cell and a six-volt 32 candle-power bulb behind a bull's-eye lens. With an empty bottle, the light is adjusted by rheostat, to give an indication of 100 on a sensitive current meter. The density of the fog is then built up until the reading falls to a convenient, arbitrary figure, such as 40% of the "empty bottle" value.

A simple and very effective means has been incorporated into the apparatus which makes it possible to keep the intensity of the light in the photoelectric density-measuring device always at its "empty bottle" value. A second photronic cell outside the bottle is illuminated by the light bulb, and is connected to a second indicating instrument. Both instruments at the start of a test are adjusted to give the same "empty bottle" indication. If, therefore, with fog in the bottle, the reading of the outside instrument is kept on this value by means of a rheostat in the lamp circuit, we can be sure that the fog density as indicated by the working photronic cell is reliable.

In actual deposition, the fog should flow past the active metal surface at a constant rate, in order to maintain a constant supply of charged particles in the immediate vicinity of the surface. It was found that 25 c.c. per second was a suitable rate of flow, and this was maintained in all deposition experiments.

The photograph in Figure 1 shows a portable form of the complete apparatus used for oil fog production, control, and deposition as a thin film on a polished metal test disc. Three five-gallon glass bottles are used, in two of which are rubber balloons. These are storage bottles for the fog immediately it is produced in one of the atomizers which can be seen on the table of the apparatus. The bottle in front is the working bottle into which the fog is fed from one or other of the storage bottles, and from which it is drawn to the deposition apparatus shown on the table at the extreme left. This ap-

paratus is shown separately in dimensional sketch form in Figure 2 and its construction is later described. In the photograph, the fog chamber is shown raised out of position. At the start of a run it is lowered into position over the deposition disc, and at the same instant voltage is applied and a stopwatch started.

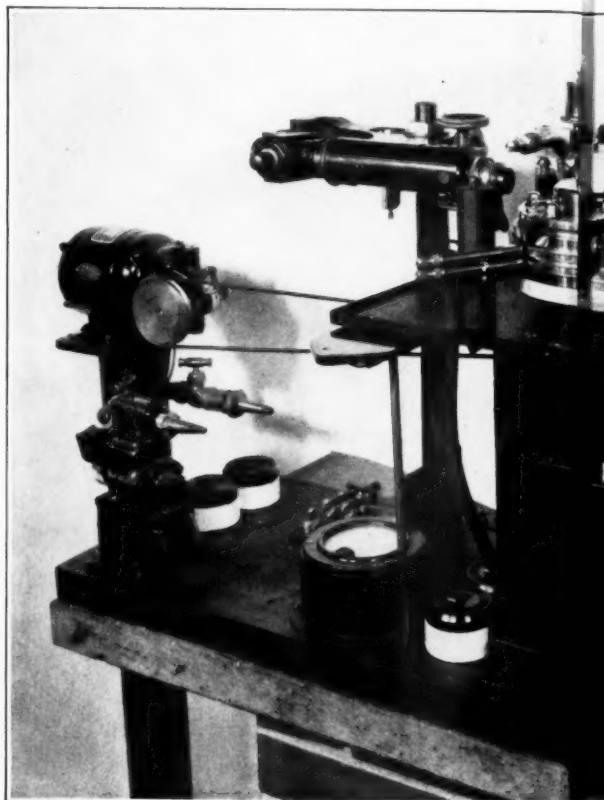


Fig. 3—Thin Test

The purpose of the balloons is to provide a means for flowing fog at a controlled rate from the storage bottle in use at the moment, into the working bottle and from thence to the deposition apparatus. To do this, nitrogen gas is fed into the balloon at a specified rate which is measured on the flowmeter seen in front of the working bottle. The expansion of the balloon serves in a very simple manner to effect the transfer of fog through the system. Stopcocks enable the operator to shift instantly from one storage bottle to the other during a long-continued calibration run with no interruption of the fog flow.

Careful attention must be paid to the uniformity of the electrostatic field around the deposition disc, in order that the oil film shall be uniform in thickness. Figure 2 shows a dimensional sketch of the deposition apparatus

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used. Oil fog of controlled density is admitted through tube (1) into a cylindrical metal box (2), the bottom plate of which is pierced with a large number of fine holes. The circular metal disc on which the thin oil film is to be laid down, forms the upper half of a pancake-shaped electrode (3), the edge of which has

the actual thickness to a considerable degree of accuracy.

The first method which suggested itself was to weigh the amount of oil deposited on a known surface area of metal, and then, knowing the specific gravity of the oil, to determine the film thickness. Theoretically, this is very easy to do, as an example will show. A certain oil, having a specific gravity of 0.8735 was deposited from fog on to the surface of a light glass ball which had been coated with a highly polished metal skin. The deposition area was 187.1 square centimeters, and in four minutes there was a weight gain of 0.8 milligram. The volume of oil deposited is therefore $0.8 / 0.8735$ thousandths of a cubic centimeter, and this, divided by the deposition surface area gives the film thickness. The film thickness in the above experiment worked out to be 4.9 millionths of a centimeter, or a little less than two millionths of an inch. Suppose for simplicity we say that the rate of deposition of the test oil was two millionths of an inch in four minutes. If, therefore, we want to produce a film $1/10$ of one millionth of an inch, which is 20 times thinner, we would expose for a time 20 times less, that is, for 12 seconds.

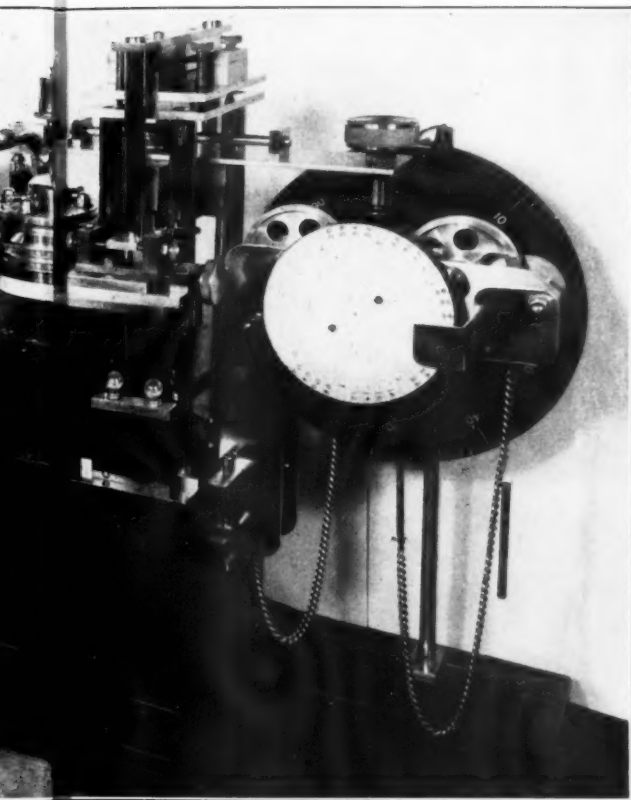
There are, however, certain practical disadvantages connected with the weighing method of estimating film thickness, the principal one being that we cannot use it in connection with the actual deposition disc we use in work to be described later. This disc with its support weighs nearly half a pound and it would be exceedingly difficult to measure with the required accuracy, the very small increase of weight due to the deposited film.

Search was therefore made for another possible method of determining film thickness which would allow the actual deposition disc to be used, and which would be both simple and accurate in use.

Colors of Thin Films

It is well known that an oil film on the surface of a water puddle sometimes shows very pure and brilliant colors. These are known as Interference Colors and are only seen when the thickness of the oil film is more than about 2 millionths and less than about 20 millionths of an inch. A film 2 millionths thick has a yellow-brown color. One 14 millionths thick shows a brilliant green. Here then, we have a very practical method of correlating thickness with color, but before we can do this accurately we must have a precise reference standard, and we must, of course, be able to produce oil films on our steel disc which exhibit color as do those on a water surface.

At this stage a very unexpected difficulty arose; the deposited oil films, although it was



—Thin Test Machine.

a radius of curvature of $1/4$ inch. The flat bottom of the fog box, and the flat upper surface of the electrode can be set very exactly to a gap distance of $1/4$ inch by means of distance pieces inserted between the ends of the sliding members (4) and the adjustable nuts (6). The electrode (3) is carried on an insulating support (5), and is connected to the 1000 volt negative side of a D.C. power pack, the positive side of which is grounded, and also connected to the metal frame. There is thus a potential gradient of 1000 volts over a $1/4$ inch gap through which the oil flows at a uniform, slow rate.

HOW FILM THICKNESS IS MEASURED

The problem to be solved was not only to lay down on a polished metal disc a thin oil film uniform in thickness, but further, to estimate

known that their thickness was of the right order, showed no color whatever. The thicker films, above about 10 millionths of an inch looked hazy, the effect being very similar to

ference colors. The hazy appearance mentioned above is caused by the fact that the film instead of being continuous, is in reality composed of myriads of tiny drops of oil. No

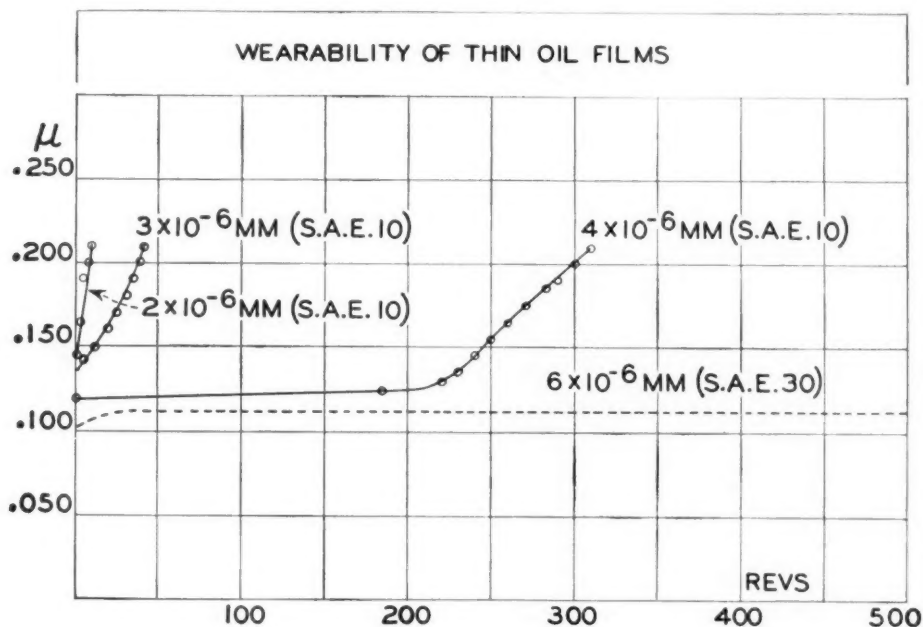


Fig. 4—Effect of thickness on wearability of thin oil films.

that produced by breathing on a cold window pane.

In order to get a clue as to the reason for this failure to produce color, it was necessary to examine very closely each step in the preparation of the steel surface before the oil film was deposited on it. So we started with a surface which was polished, but not clean. The presence of a greasy film could be shown by the fact that water poured on the surface would shed almost completely, leaving an apparently dry surface. An oil film only one molecule thick is sufficient to prevent the wetting of a surface of highly polished metal. Such a film of oil will not be removed by washing with solvents such as benzene or carbon tetrachloride but can easily be removed by scouring with a paste of fine optical rouge and water, or with a metallographic powder such as "Shamva", and water.

But then comes the real difficulty—that of removing the last traces of the polishing powder. It might be thought that scrubbing the surface with a series of absorbent cotton pads under running water would be sufficient, but very surprisingly it is found that a surface finished in this way will not serve as a base on which to deposit an oil film showing inter-

ference colors unless the film has a continuous upper and lower surface as is the case when it lies on water.

A little thought suggested that the reason for the droplet formation might be the presence of dust particles too small to be seen even under the microscope, but which would, each one of them, act as focal points around which oil would collect. It is well known that fine powder particles are very strongly attached to clean surfaces, and this suggested the necessity of adopting a more vigorous scrubbing action in order to remove them. The problem was finally solved by the use of rubber gloves, made perfectly free from oil by dipping in cleaning solution followed by thorough washing in water. The metal deposition disc, held in the gloved fingers of one hand is vigorously rubbed with the gloved fingers of the other, under hot running water. After a final flushing with distilled water to ensure that the surface when dry does not carry traces of salts from the tap water, the disc is washed in hot absolute alcohol to remove the attached water. After such treatment an oil film in the proper thickness range, deposited on the surface prepared in this way, shows brilliant and uniform interference colors.

Making a Standard Thickness-Color Gage

As previously mentioned, before we can be sure what the various colors of thin films actually mean in terms of thickness, we must build a reference gage. This is a strip of highly

sary to make a small correction for the index of refraction of Barium Stearate as compared with that of lubricating oil.

How the Thickness-Color Gage is Used

The problem is, as before stated, to lay down on the surface of a clean and highly polished steel disc, a film of lubricating oil which shall have an accurately known thickness of, say, one-tenth of one millionth of an inch. To do this, the disc is placed in the deposition apparatus shown at the left in the photograph, Fig. 1, and in detail in Fig. 2. After the fog has been brought to proper density, a stop-watch is started marking the beginning of exposure. For simplicity of calculation, let us say that Green in the table corresponds to a thickness of 14 millionths of an inch, and that a perfect match with the Green of the standard color gage is obtained after 2800 seconds exposure. Since it is known that film thicknesses are proportional to exposure times, a simple calculation shows that our required thickness of one-tenth of one millionth would be deposited in 20 seconds.

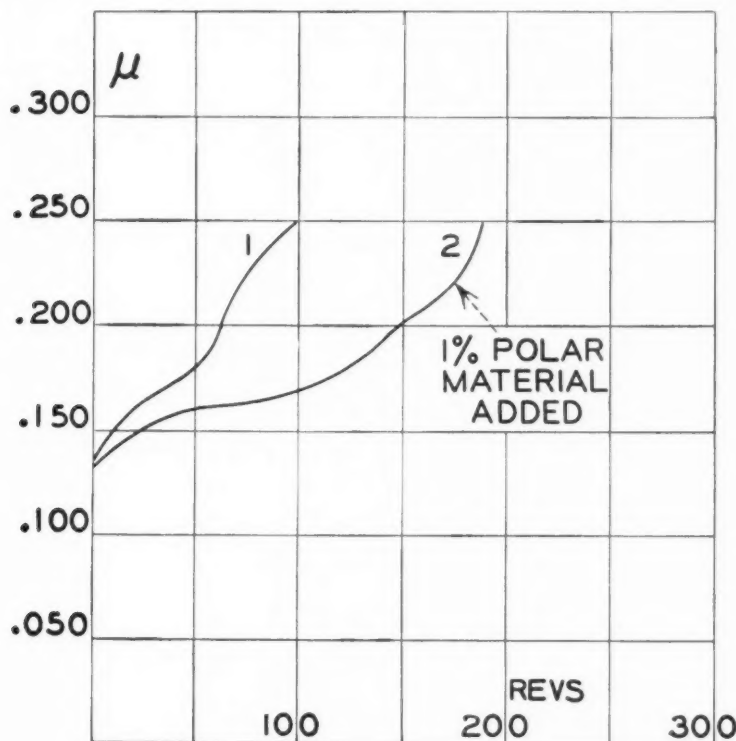


Fig. 5—Effect of an addition agent on wearability of a thin oil film.

polished chromium-plated metal on which a number of color steps, which are really thickness steps, have been laid down. This is done by the very beautiful and simple method perfected by Langmuir and Blodgett of the General Electric Research Laboratory. Each step of the gage consists of a known number of layers of molecules of Barium Stearate, lying neatly in contact, like a pile of flat papers. The important fact about these layers of molecules is that the thickness of each layer is known to a considerable degree of accuracy, and therefore, knowing the number of layers forming each step, we know the thickness of every step along the gage. Table I is taken from data published by Blodgett.

It will be noticed that if these thicknesses are converted into inch measure, they start with approximately 2 millionths for the first step and increase by approximately the same amount for each succeeding step. It may be mentioned that for greater precision it is neces-

What has been said hitherto has dealt mainly with the problem of depositing an oil film of known thickness on a polished steel test disc. The further problem now is to test the resistance of this thin film to mechanical attack. The most logical and convenient method of doing this is to follow the progressive rise of friction when a suitable rubbing "point" is passed repeatedly over the same track. It is found that during the course of a test the coefficient of friction rises, usually very slowly at first and finally quite rapidly. The initial value of the coefficient for an average straight mineral oil in the form of a film 1/10 of a millionth of an inch thick, is about 0.130. Toward the end of the run, after the coefficient passes 0.200, the value rises to 0.250 in the course of only a very few passages of the rubbing point over the track.

It is convenient to take 0.200 as the breakdown point, and to report the number of passages as the Wearability value of the oil.

WEARABILITY OF THIN OIL FILMS

The rubbing "point" in this test is a rounded, and very highly polished sapphire, the radius of curvature of which is 1/16 inch. A load of 100 grams is applied, and the circular test disc slowly rotates under the sapphire, which is offset with respect to the axis of rotation of the horizontal disc. Calculation shows that the intensity of pressure at the rubspot is somewhat higher than 100,000 pounds per square inch. Under these circumstances we may expect the oil molecules to be gradually dragged loose from their attachment to the steel. We may also expect, if the film is thick enough, that oil molecules adjacent to the track, will flow in to replace those rubbed off, thus reducing the rate at which the coefficient of friction rises, and delaying the breakdown point.

of the addition of 1% of a material of marked polar activity.

Thin Film Wearability Machine

The photograph in Figure 3 shows the Thin Film Test Machine set up for operation, and Figure 6 is an elementary schematic diagram showing the essential features. A nicely balanced horizontal bar is so suspended as to have only two degrees of freedom.

1. It can rock freely in a vertical plane about a line defined by knife edges at right angles to the length of the bar.
2. It can move in the direction of its length, the amount of movement being limited by stops which serve also as electric contacts thus providing a means of indicating de-

TABLE II
Comparison of Static Coefficients (S) and Running Coefficients (R) for
Three Different Oils on Steel and Bronze

Oil	S	Tests on Steel	
		R	(R-S) per cent difference
A	0.116	0.100	-13
B	0.083	0.093	+12
C	0.090	0.100	+11
Oil	S	Tests on Bronze	
		R	(R-S) per cent difference
A	0.086	0.100	+16.5
B	0.051	0.088	+56
C	0.069	0.095	+38

The effect of variation of film thickness is very marked, there being a quite disproportionate increase in the life of the film as its thickness increases. The graphs in Fig. 4 show the effect of varying thickness of films of a straight mineral oil of S.A.E. 10, on the resistance to mechanical wear. The full lines refer to films 2, 3, and 4 millionths of one millimeter thick respectively. The dotted graph was from another test in which the oil used was S.A.E. 30 and the thickness was 0.25 millionths of an inch, or slightly over 6 millionths millimeter. After a slight initial rise, the coefficient remains quite constant over the period shown. As a matter of fact this particular test was continued for 2000 revolutions of the disc, without any change in the coefficient.

The graphs in Figure 5 show the effect of an addition agent on the resistance to wear of a thin film, and suggest this means of increasing the protective action of an oil against the risk of failure when fluid film conditions give place to boundary film conditions.

Line 1 shows the progressive rise of the coefficient of friction for a straight mineral oil of S. A. E. 30 grade in a film approximately two molecules thick. Line 2 shows the effect

parture from a neutral or balanced position.

Near one end of the bar is a holder carrying a round-faced rubbing button which rests on the outer portion of the circular test disc, the latter being fixed on the top of a rotating table offset with respect to the center line of the bar. As the table rotates, the button traces out a true circle on the face of the test disc. The working load is a 100 gram weight placed on the top of the button holder. At the other end of the balance bar is attached a silk thread which passes in a left and right direction over two frictionless pulleys to a double chainomatic device by means of which a pull, P, can be applied to the bar, equal in amount and opposite in sense, to the drag of friction, F, between the rubbing button and the face of the rotating test disc. If the frictional drag exceeds 10 grams a 10-gram weight is hung on the outermost chain. A simple gear operated by turning the graduated dial allows the chain to be lowered on the right and raised on the left, which operation increases the pull on the silk thread in the direction opposed to the frictional drag. The machine is sensitive to an out of balance setting of 0.1 gram, which means that

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with a load of 100 grams, the coefficient of friction can be determined to better than one per cent. The exact point of balance is determined by observing the needle of a microammeter which moves left or right of zero when left or right contacts are made at the limit stops already referred to. The free gap at each of these contacts which are faced with polished

THE COEFFICIENT OF STATIC FRICTION

Suppose we place a solid body of any kind on a flat horizontal surface and, by means of a cord pulling in a horizontal direction measure the force just sufficient to start the body moving. This force is equal to the friction at the instant of initial slip, and if we divide it by

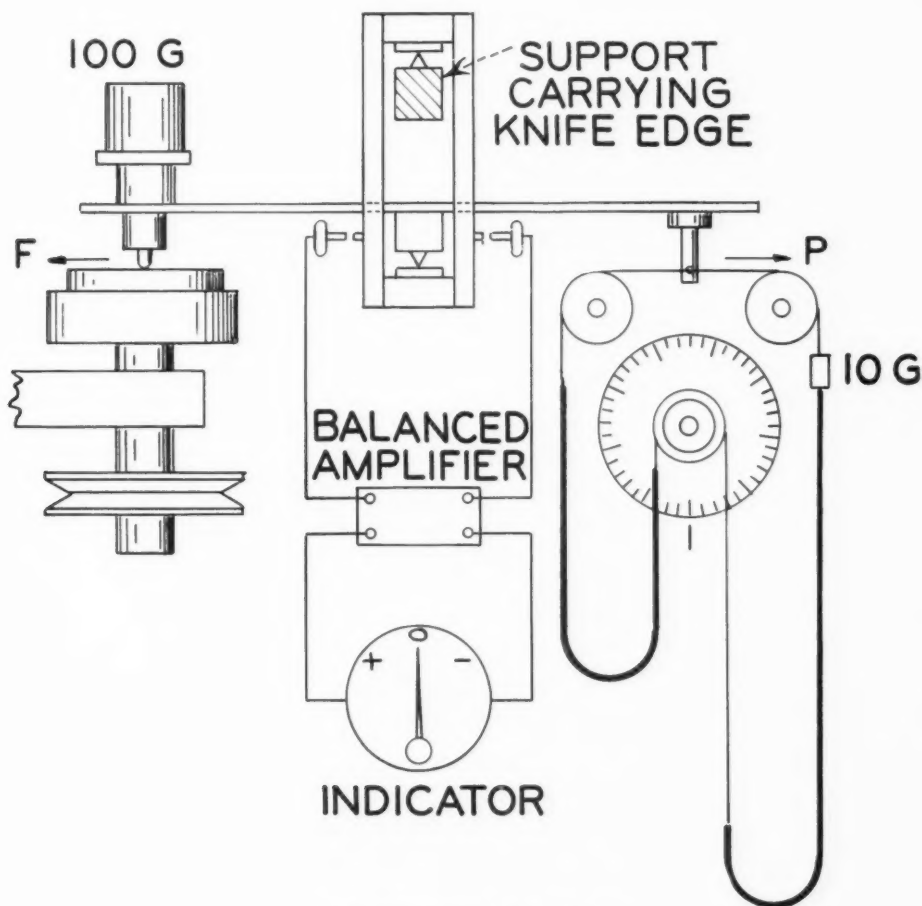


Fig. 6—Schematic details of Oil Film Tester.

tungsten, is slightly greater than 0.0005 inch, and entire freedom from the effect of resistance changes at the contacts is secured by the use of a simple two-tube radiotron circuit, the balance of which is upset when either contact is made.

A scale around the circumference of the rotating table on which the test disc is mounted is divided into 10 equal parts numbered from zero to nine. This scale is useful when determining the value of the coefficient of static friction at various points around the track circle as will be described later.

the weight of the slipping body, the number obtained is called the coefficient of static friction.

By means of the machine described, it is possible very easily to find the coefficient at any portion of the circular track. The coefficient may vary slightly around the circle owing to small differences in the state of the steel surface. The value reported is the average of the coefficient determined at 10 equally spaced stations around the track.

In making a measurement of the coefficient

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of either running or of static friction under thin film conditions, it is not necessary to pay any attention to the amount of oil used. A drop of the test oil is applied to the track and is spread around by means of a glass rod. During the test, no matter how thick the layer is on the steel, the actual film between the rubbing point and the flat surface is exceedingly thin, probably not more than two molecules thick. The reason for this is that all excess oil has been squeezed out at the contact spot by the excessively high unit pressure.

WHAT IS MEANT BY THE TERM OILINESS

Of late years a great deal has been heard about Oiliness. It is usually assumed that it is a property of a lubricant which will reduce friction, but this is only partly true. For instance, it is not correct to say that one oil,

under normal operating conditions, there is absolutely no oiliness effect. The only property of the lubricant affecting friction is its actual viscosity at the temperature and pressure existing in the film.

STATIC FRICTION vs. RUNNING FRICTION

It is usually believed that static friction is higher than running friction, but like so many other widely quoted concepts this one is subject to considerable modification. In examining the facts we must confine our attention to the case of very thin films. Tests show quite definitely that if the oil-metal system has marked oiliness, the static friction is distinctly less than the running friction. The table on page 142 gives the results found with 3 oils run on Steel and Bronze. Two of the oils, B and C, contained a material of marked

TABLE III
Effect of Surface Activity of Metal, and of Molecular Activity of Oil, on the Coefficient of Static Friction

<i>Oil</i>	<i>Steel</i>	<i>Bronze</i>	<i>Per cent Reduction</i>
A—Straight Mineral Oil	0.116	0.086	26
B—Same oil plus 0.5% of an active material	0.083	0.051	39
Per cent Reduction:	29	41	

A, is superior in oiliness to another oil, B, because if we test them out, we may find we actually get greater friction with A than with B. The explanation is that the nature of the metals to which the oil is attached plays an equally important part in the phenomenon called Oiliness.

Another fact, not as widely known as it should be, is that this property of Oiliness is not noticeable until the film is very thin—that is, of dimensions probably less than a millionth of an inch. The thinner the film is, the greater the oiliness effect until, with a film only two molecules thick we reach the maximum effect, or in other words we observe the minimum value of the coefficient of static friction. This latter statement is made advisedly because it is found that the static coefficient is more sensitive to the effect of the Oiliness property of an oil-metal partnership than is the running coefficient.

With thick films such as are built up between the rubbing surfaces of a machine running

chemical activity, that is, one which contributes greatly to the Oiliness effect, while Oil A was a straight mineral oil. Incidentally, the effect of the Bronze on the Oiliness property will be seen to be quite marked. Oil A used with steel shows the running coefficient to be 13% less than the static when steel is the metal used, but with bronze, the running coefficient is 16.5% greater than the static.

The effect on the Coefficient of Static Friction of the addition of an "oily" constituent to the oil, and also by the use of an "active" metal such as bronze, is well shown in the above table, where the figures for the static coefficient found for Oils A and B used with Steel and Bronze have been rearranged.

These figures show very strikingly that the Oiliness effect is not a property of the oil alone, but of the metal also. In other words, it is a partnership effect. Further, it is a property which produces its maximum effect only when the film of oil is very thin, and is best shown by a determination of the coefficient of static friction.

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the Selection and Use of Lubricants

THIS ISSUE

Thin Oil Films



PUBLISHED BY
THE TEXAS COMPANY
TEXACO PETROLEUM PRODUCTS

LUBRICATION MEASURED TO A *millionth* OF AN INCH

REMARKABLE work is being done by machinery builders in perfecting the finish on bearing surfaces. Accuracies are being attained in the grinding and polishing of high-speed bearings which have never before been possible. Variations may be measured by millionths of an inch. Extended running-in periods are no longer so essential. This perfection of final machining has a direct bearing on lubrication.

Accurate grinding and polishing of bearing surfaces makes possible the highest degree of lubrication efficiency.

Thin oil film lubrication has, therefore, been given intensive study in relation to surface finish and the practical application to problems of manufacturers.

The accompanying article in this issue indicates the extent of this research at The Texas Company's Beacon, N. Y. laboratories in developing methods for measuring and evaluating thin oil films and their influence under high speeds, temperatures, and pressures.

In this work, The Texas Company is fully cooperating with manufacturers, freely opening its research data to promote better lubrication and higher efficiency in bearing design and manufacture.

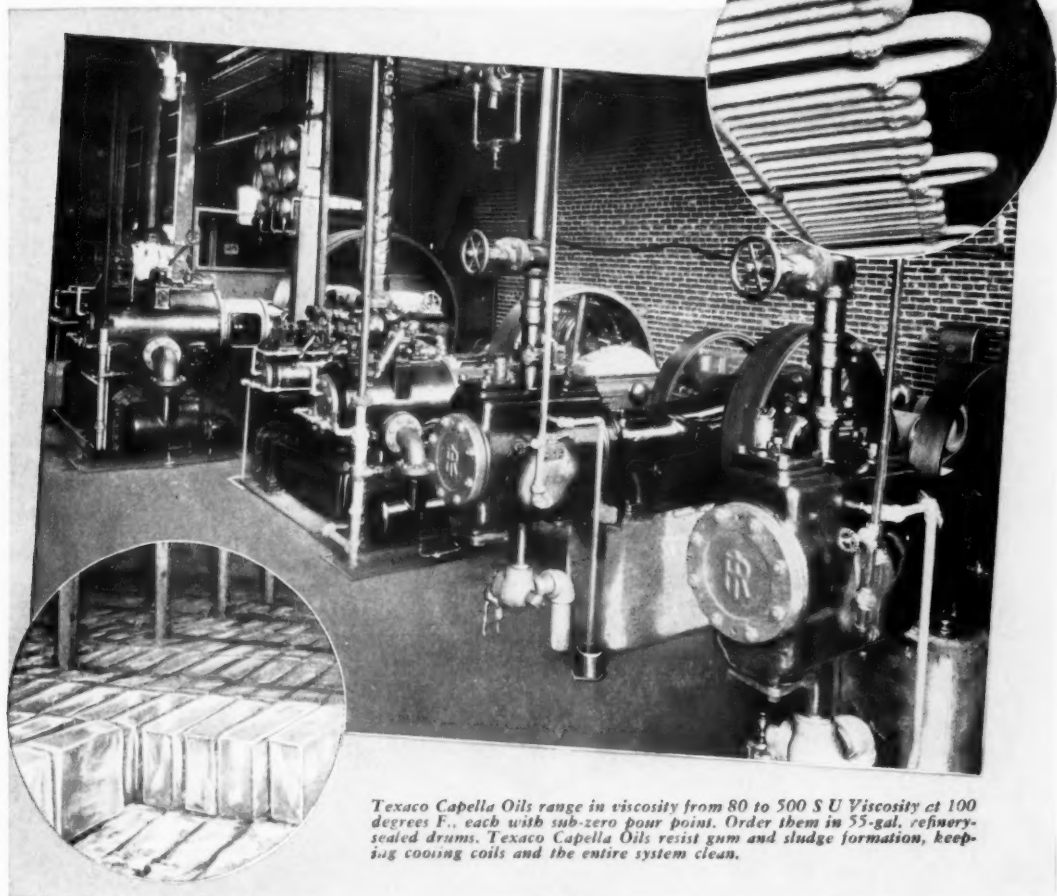


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Texaco Capella Oils range in viscosity from 80 to 500 S U Viscosity at 100 degrees F., each with sub-zero pour point. Order them in 55-gal. refinery-sealed drums. Texaco Capella Oils resist gum and sludge formation, keeping cooling coils and the entire system clean.

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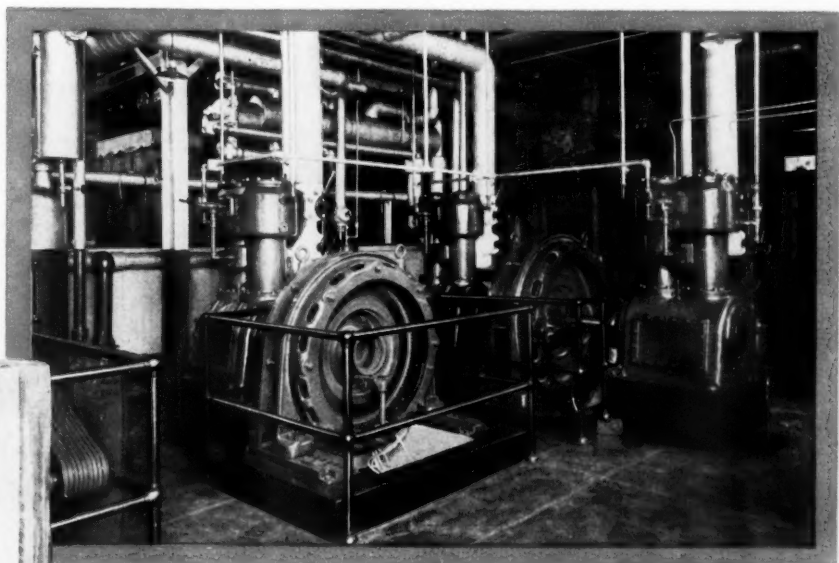
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EXCEPT in the compressors, oil in any other part of your refrigerating system is undesirable. To make sure that the oil you use drops out rapidly from the hot refrigerant in the oil separator, use Texaco Capella Oils.

All six viscosity grades of Texaco Capella Oil have sub-

zero pour points. They are free from moisture, and do not react with refrigerants.

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